Stability Improvement of SMIB &Multimachine System using PSO Tuned SSSC Controller

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***Abstract*- In this paper, the PSO technique is employed for designing the damping controller based on static synchronous series compensator for improving the stability of power system. In modern power system, stability is a key issue for planning and secure operation. Over the last few decades the demand of power has increased rapidly. In order to meet this rapidly increasing demand either new transmission lines & generating stations are to be installed or the operation of existing network has to be pushed to limits. The building of new transmission line and generating station is limited by financial and environmental constraints. As a consequence, the existing network is to be loaded heavily which presents the threat of instability. The present thesis work investigates the design of a Static Synchronous Series compensator for improving the stability of a single machine infinite bus system and a multi-machine system. The design of lead-lag structured SSSC based damping controller is formulated as optimization problem. The optimal parameters for the proposed controller are obtained using particle swarm optimization (PSO). For SMIB system the robustness and effectiveness of PSO optimized SSSC damping controller is evaluated under various operating conditions viz. light, nominal and heavy loading for various disturbances like 3-phase, L-L, L-L-G, L-G and small disturbance with the objective of minimizing the speed deviation. In case of multi-machine system the effectiveness of PSO optimized SSSC damping controller is tested for various faults with the aim of reducing the inter area mode of oscillations. The simulation results presented through various graphs validated that PSO optimized SSSC damping controller reduces the settling time of system post disturbances and therefore enhances the system stability.**

KeyWord: FACTSdevices,SSSC,SMIB,MultimachineSystem, PSO Technique

I. INTRODUCTION

Modern power systems are widely interconnected and complex. These large and complex power systems are connected with each other by weak tie lines, as a result low frequency oscillations are observed in such systems. In absence of effective damping the oscillations may sustain and grow up with time and finally causing the system separation. The large scale usage of flexible AC transmission system (FACTS) controller has emerged in power system because of recent advancement in power electronics. The unique feature of FACTS controller to control the network condition in a rapid manner can be used for improving power system stability. The static synchronous series compensator (SSSC) is one of the most widely used FACTS controller which is installed in series with a line. The SSSC can effectively control the flow of power in a line because of its ability to change its reactance characteristics from inductive to capacitive. The use of SSSC controller for frequency stabilization, stability improvement and power oscillation damping can be seen in many references. The effect of mode of operation i.e. inductive or capacitive and degree of compensation by SSSC on stability has also been already cited in many references. Many of such proposals are based on small disturbance analysis which demand linearization of the system considered. But the complex dynamics of power system are not covered by linear methods mainly for major disturbances. This condition puts forward problem in tuning of FACTS controller because the controllers which are tuned to perform for small signal conditions do not work satisfactorily for major disturbances. In addition to this, with the linear single phase models the behavior of controller for unbalanced faults can't be identified. Therefore to resolve this problem in this thesis we have considered three phase models of various power system components and SSSC controller.

The power system utilities prefer conventional lead-lag structured controller because it offers lot of advantages like easy dynamic modeling, on line tuning and minimum efforts for development. A large number of standard conventional methods are available for design problem of controllers like modern control theory, eigen value assignment & mathematical programming. But these conventional approaches have some problems like they consumes lot of time since iterations are more, need large computation burden and have slow convergence. Also conventional techniques have possibilities that the search process can be limited to local minima and optimal solution may not be obtained.

Since the last few years particle swarm optimization technique (PSO) is preferred by researchers for optimization problems. PSO is mainly a population contingent stochastic optimization algorithm. The PSO algorithm is influenced from the social behavior of fish schooling of bird flocking. PSO is similar to genetic algorithm (GA) in many aspects like initialization of population and searching of optimal solution by updating population. But PSO does not use evolution operators like mutation and crossover which are used by GA. PSO offers many advantages over GA like simple algorithm – can be easily implemented and it uses few parameters. In the present thesis work PSO is used for optimizing the parameters of SSSC based controller.

In this thesis work, the effectiveness of SSSC based damping controller for improving the system stability is assessed under different disturbances for single machine infinite bus system and multi-machine system. The parameters of SSSC controller are optimized by using PSO algorithm.

A. Structure of SSSC Controller

The design of SSSC controller based on lead lag structure to determine the SSSC injected voltage Vs is depicted in fig. 1.

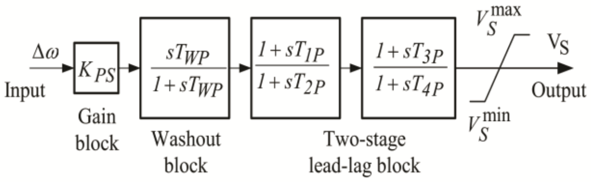

Fig. 1 Structure of SSSC Controller

The lead lag controller has many advantages like high reliability, simple structure, easy dynamic modeling and minimum efforts for development. The input signal to the controller is speed deviation dw and the output signal of controller is injected voltage Vs. It comprises of a gain block K, phase compensation block & signal wash out block.

The signal washout block is basically a high pass filter which is having a time constant of T_{WP}. The value of T_{WP} should be sufficiently high so that signals related with real power oscillations are passes without change. Hence it controls the steady change in real power. The value of T_{WP} can be in the range of 1 to 20 sec. In the present study it is assumed as 10 sec.

The phase compensating block is having time constant of T_{1P}, T_{2P}, T_{3P} & T_{4P}. The phase compensation block helps in compensating phase lag between output and input signal by providing necessary phase lead characteristics

B. Problem Formulation

The lead lag structured SSSC controller has transfer function given by

$$U_{SSSC} = K.\left(\frac{s.T_{wp}}{1+T_{Wp}.s}\right)\left(\frac{T_{1p}.s+1}{T_{2p}.s+1}\right)\left(\frac{T_{3p}.s+1}{T_{4p}.s+1}\right)y \qquad (1)$$

In the above structure the values of T_{WP}, T_{2P} and T_{4P} are usually specified. In the present thesis work values $T_{WP} = 10$, $T_{2P} = 0.3$ & $T_{4P}=0.3$ are used. The gain K and time constant T_{1P} & T_{3P} are to be find out. The injected voltage Vq is modulated during dynamic conditions to damp oscillations. The value of Vq during dynamic condition is

$$V_s = V_{ref} + \Delta V_s \qquad (2)$$

C. Objective Function

When a large disturbance occur in power system, power system oscillations are originated. These oscillations appear as deviation in the line power, rotor speed or power angle. Hence the objective function can be to minimize any of these deviations. In this paper the objective function is to minimize the speed deviation. For single machine infinite bus system, the objective function is taken as integral time absolute error of speed deviation and for multi-machine system the objective function is integral time absolute error of speed deviation for inter area mode of oscillations.

The objective function for single machine infinite bus system is

$$J = \int_0^t |\Delta w|.t\,dt \qquad (3)$$

The objective function for multi-machine system is

$$J = \int_0^t |\Delta w_I|.t.dt \qquad (4)$$

In equation 3 Δw denotes the speed deviations for SMIB system and t is the simulation time range. In equation 4, $\Delta w_I(\Delta w_I = \Delta w_1 - \Delta w_2)$ is the speed deviation for inter area mode of oscillations for multi-machine power system. It is aimed that above mentioned objective functions of eq. 3 & 4 are minimized so that the system response in terms of settling time is improved.

Minimize J subjected to

$$K^{min} \le K \le K^{max} \qquad (5)$$

$$T_{1P}^{min} \le T_{1P} \le T_{1P}^{max} \qquad (6)$$

$$T_{3P}^{min} \le T_{3P} \le T_{3P}^{max} \qquad (7)$$

The above mentioned parameters of SSSC damping controller are optimized using PSO algorithm.

II.STATIC SYNCHRONOUS SERIES COMPENSATOR

SSSC is a widely used member of FACTS family. The concept of SSSC was first introduced by Gyugyi in 1989. The SSSC is basically a solid state voltage sourced converter based series compensator having the ability to generate controllable AC voltage. The SSSC is basically installed in series in the power system. The SSSC injects a voltage in series in the line. The voltage injected by SSSC i.e. Vq is in quadrature with the line current I.

The SSSC can effectively control the flow of power in a line because of its ability to change its reactance characteristics from inductive to capacitive. The operation of SSSC as inductive or capacitive reactive compensator is dependent on magnitude of injected voltage. The functional model of SSSC is shown in fig. 2.

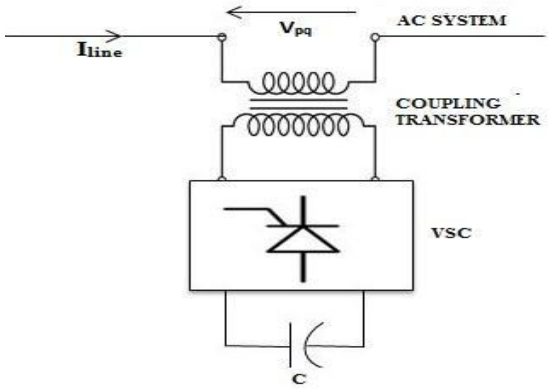

Fig.2 Static Series Compemstator

From the functional model of SSSC shown in fig.2 it can be seen that SSSC is coupled to transmission line by a coupling transformer which is basically a boosting transformer. This boosting transformer is connected to a voltage source converter (VSC). The amplitude of voltage sourced converter can be changed. If the amplitude of VSC is increased then there will be power from SSSC controller to the line thereby generating reactive power. If there is a reduction in the VSC amplitude, then current flow from line to controller and hence absorbtion of power takes place.

Consider a single line diagram of a two machine system with a series capacitive compensated line as shown in fig. 3 below along with the phasor diagram.

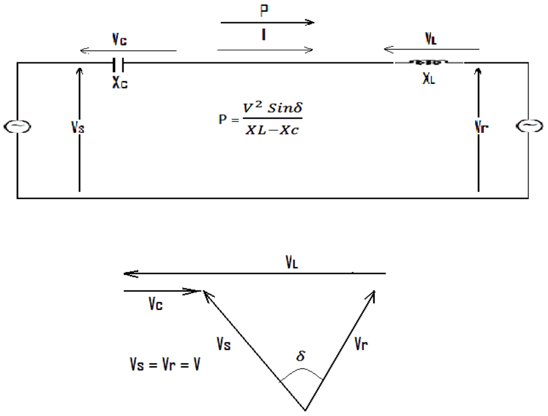

Fig. 3 Two machine system with series capacitive compensated line & phasor diagram

It can be seen from phasor diagram in fig. 3 that for a given value of line current, the opposite polarity voltage across the series line reactance is forced to increase by the voltage across the capacitor. Hence the conventional series capacitive compensation basically has the effect of increasing the voltage across the series impedance of a line. As a consequence the line current and power transmitted are also increased.

Conventionally series capacitive compensation can be considered a way of decreasing the line impedance while in reality it is basically a way to increase voltage across the impedance of a line. Hence it can be concluded that the same steady power transfer can be achieved if series compensation is accomplished by a synchronous ac voltage source as shown in fig. 3. The output of synchronous ac voltage source is precesily same as of series capacitor.

$$V_q = V_c = -jxI = -jkxI \qquad (8)$$

Where Vc = Injected compensating voltage phasor
I = line current
Xc = reactance of series capacitor

A. *Single Machine Infinite Bus System with SSSC*

In fig. 4 single line diagram of a single machine infinite bus system with SSSC which is considered to carry out the study is shown.

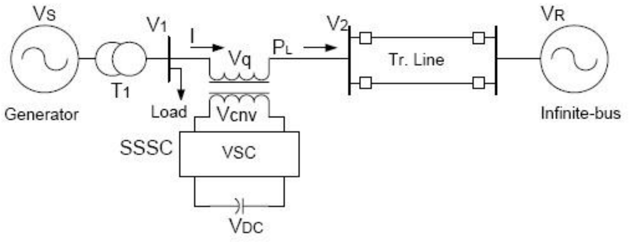

Fig.4 SMIB System with SSSC

The SMIB system in fig. 4 consists of a generator, a step up transformer, a SSSC controller and a double circuit transmission line. The generator is supplying an infinite bus through a step-up transformer and a SSSC followed by a double circuit transmission line. In fig. 4 T1 is a step up transformer, Vs is generator terminal voltage, V_R is terminal voltage of infinite bus and VDC is a DC voltage source.

The SSSC injects a voltage Vq in series with transmission line, which is having quadrature phase displacement with line current. The supply or absorbtion of active or reactive with system is influenced by phase displacement between voltage Vq and line current I. By varying the magnitude and polarity of injected voltage Vq the level of compensation can be controlled. The injected voltage Vq is varied by a voltage source converter which is connected to the secondary of a boosting transformer. The VSC is made from a forced commutated power electronics device like IGBT, GTO etc. The VSC has a DC capacitor connected to it which works as a dc voltage source. The SSSC draws a small amount of active power from the system so that the losses of VSC and boosting transformer can be supplied and the capacitor remains charged.

B. *Two Machine System with SSSC*

Fig. 5 shows the single line diagram of two machine system which is considered for carrying out the study. The system consists of two generating units of 2100 MVA & 1400 MVA. The two machine are connected with the help of transformers and transmission lines. The machine of 2100 MVA rating is connected to a step up transformer of 2100 MVA, 13.8KV / 500 KV and the machine of 1400 MVA is connected to a step up transformer of 1400 MVA, 13.8 KV / 500 KV. A 100 MVA SSSC is installed near bus 2 in series with transmission line with the help of a coupling or boosting transformer.

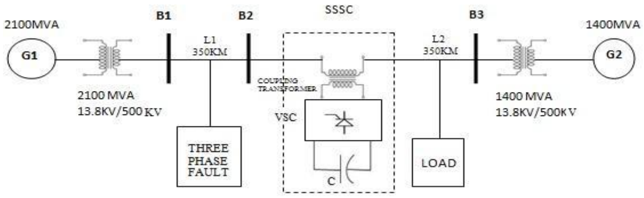

Fig.5 Single Line Diagram of Two Machine System

III. PARTICLE SWARM OPTIMIZATION TECHNIQUE

Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Dr. Ebehart and Dr. Kennedy in 1995, inspired by social behavior of bird flocking or fish schooling. PSO shares many similarities with evolutionary computation techniques such as genetic Algorithms (GA). The system is initialized with a population of random solutions and searches for optima by updating generations. However, unlike GA, PSO has no evaluations operator such as cross over and mutation. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles. PSO has been successfully applied in many areas: function optimization, artificial neural networking training, fuzzy system control and other areas where GA can be applied.

The PSO technique conducts searches using a population of particles, corresponding to individuals. Each particle represents a candidate solution to the problem at hand. In a PSO system particles change their positions by flying around in a multidimensional search space until a relatively unchanged position has been encountered or until computational limitations are exceed.

The advantages of PSO over other traditional optimization techniques can be summarized as follows:

- PSO is a proportional based search algorithm. This property ensures PSO to be less susceptible to getting trapped on local minima.
- PSO uses payoff information to guide search in the problem space. Therefore PSO can easily deal with non-differentiable objective functions..
- PSO uses probabilistic transition rule and non-deterministic rules. Hence, PSO is a kind of stochastic optimization algorithms that can search a complicated and uncertain area. This makes PSO more flexible and robust than conventional methods.
- Unlike GA and other heuristic algorithms, PSO has the flexibility to control the balance between the global and local exploration of search space.
- Unlike the traditional methods, the solutions quality of proposed approach does not rely on the initial population. Concept of modification of a searching point by PSO is shown in fig.6

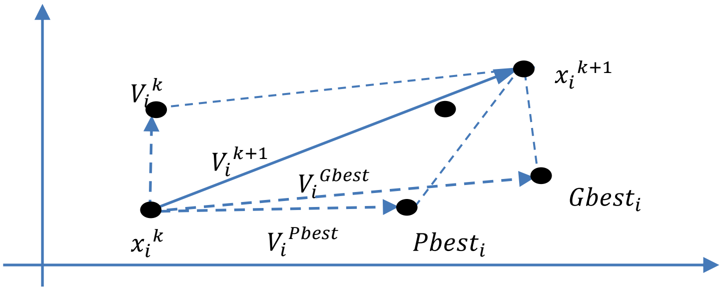

Fig. 6: Concept of Modification Of A Searching Point by PSO

Where
xk : Current position,
xk+1 : Modified position,
Vk : Current velocity,
Vk+1 : Modified velocity,
V_i^{Pbest} : Velocity based on Pbest,
V_i^{Gbest} : Velocity based on Gbest

For each particle, at the current time step, a record is kept of the position, velocity and the best position found in the search space so far. Each particle tries to modify its position using the following information:

- The current positions
- The current velocities
- The distance between the current position and Pbest
- The distance between the current position and Gbest

IV. MATLAB/SMULINK Implementation of SMIB & Multi-Machine System with SSSC

Fig.7 and Fig.8 shows the matlab model of single machine infinite bus system and multi-machine system with SSSC controller. The models have been designed using simpower system toolbox of MATLAB / Simulink. SimPower system is a widely used MATLAB based design tool used by engineers & scientists to build models and for simulation.

The Simpower system tool consists of models of various equipments like machines, governors, transformers, excitation system, FACTS devices and transmission lines. It also consist of a powergui block which is required for simulation of a model having simpower system blocks. The powergui block performs load flow & machine initialization.

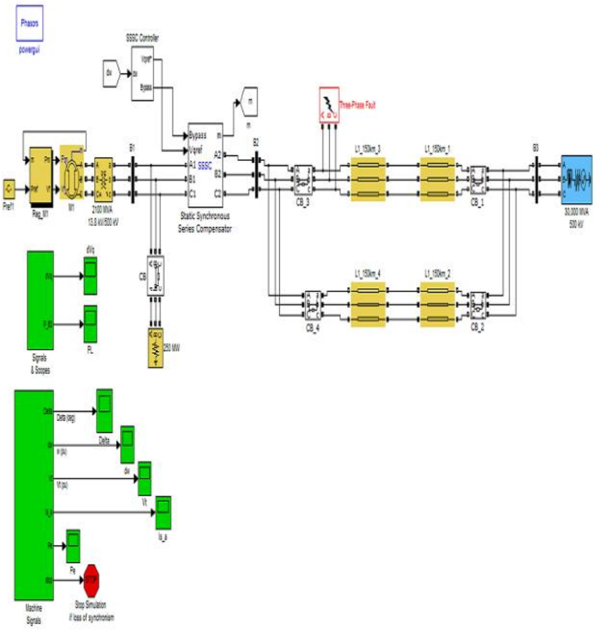

Fig. 7 Matlab model of SMIB system with SSSC Controller

Fig. 7 shows the MATLAB model of a SMIB system with SSSC controller. The system comprises of a hydraulic generating unit of 2100 MVA, 13.8 KV, 60 Hz. This generator is supplying an infinite bus through a step-up transformer of 13.8 KV / 500 KV, a 100 MVA SSSC and a double circuit transmission line of 300 km. The generator is provided with a hydraulic turbine & governor (HTG) and excitation system.

Fig.8 shows the model of two machine system. Two hydraulic generating units M_1 and M_2 of 2100 MVA & 1400 MVA are used. The transmission lines are used to connect the load and the machines. A 100 MVA SSSC is connected near bus B2. There are three buses (B1, B2, B3) connected through the transmission lines L1, L2 separately. The faults are created near the bus B1 using fault breaker.

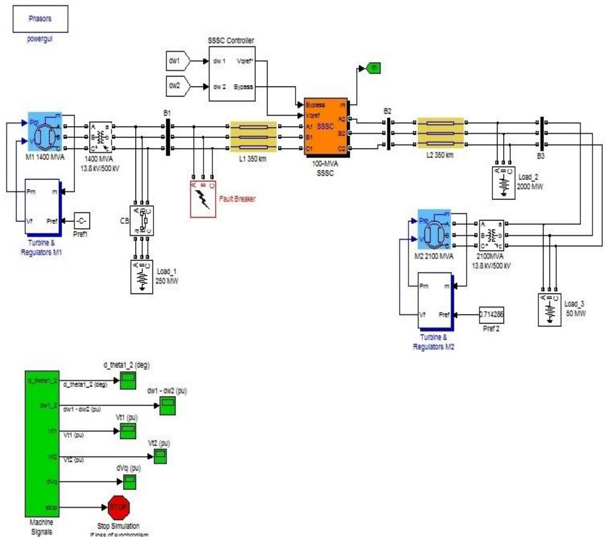

Fig.8 Matlab model of Two machine system with SSSC controller

V. RESULT ANALYSIS & DISCUSSION

The developed model is simulated without SSSC controller and with PSO tuned SSSC controller. The responses with and without controller are accessed to test the effectiveness and robustness of the SSSC damping controller and its performance for a wide range of operating conditions for different faults.

The Simulation studies are carried out on two systems, one is single machine infinite bus (SMIB) system and the other one is a two machine (multi-machine) system. In case of SMIB system the behavior of the PSO tuned SSSC controller is tested under different operating conditions viz. nominal loading, light loading & heavy loading by applying different types of fault and for multimachine system the effectiveness of controller is examined for various contingencies.

Condition 1:- Single Machine Infinite Bus System

I. Nominal Loading

The effectiveness of PSO optimized SSSC controller for damping the oscillation is first accessed at nominal loading condition (Pe = 0.75pu, δ_0 = 48.9) under different faults and small disturbances.

From fig.9 to 13 shows various wavefom of the simulation results of SMIB system at nominal loading without and with PSO tuned controller for three phase fault,L-L-G fault,L-L fault,L-G fault and small disturbance. It comes out that the PSO optimized SSSC based controller improves the system stability by damping out the oscillations and enabling the system to settle down quickly after various faults, whereas the system without controller takes longer time to settle down.

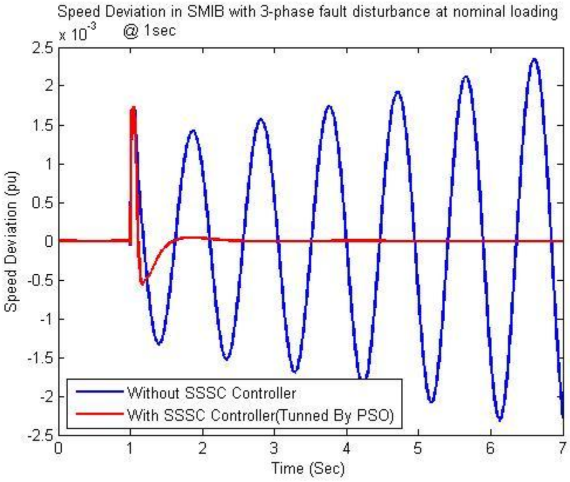

Fig. 9: Speed deviation in SMIB for 3-phase fault with & without SSSC controller at nominal loading

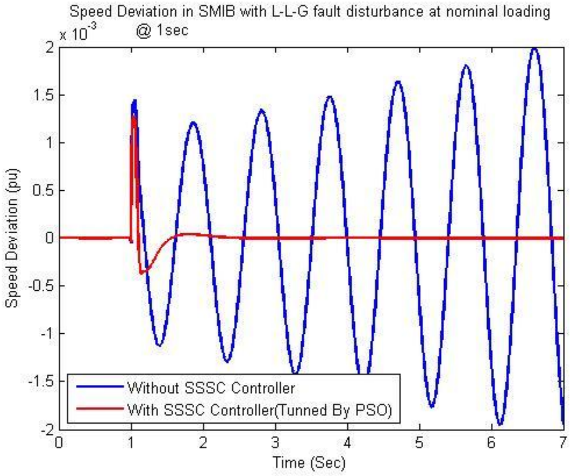

Fig. 10: Speed deviation in SMIB for L-L-G fault with & without SSSC controller at nominal loading

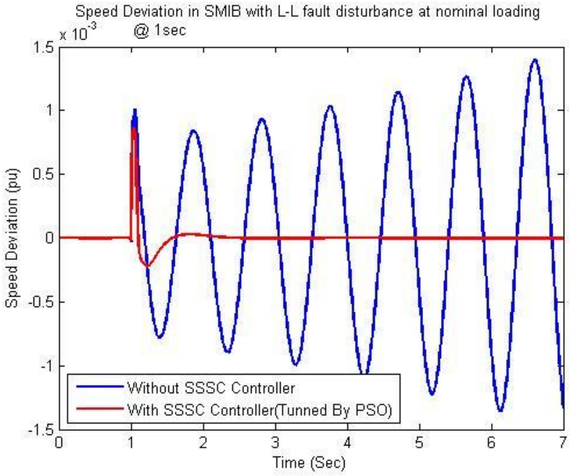

Fig. 11 Speed deviation in SMIB for L-L fault with & without SSSC controller at nominal loading

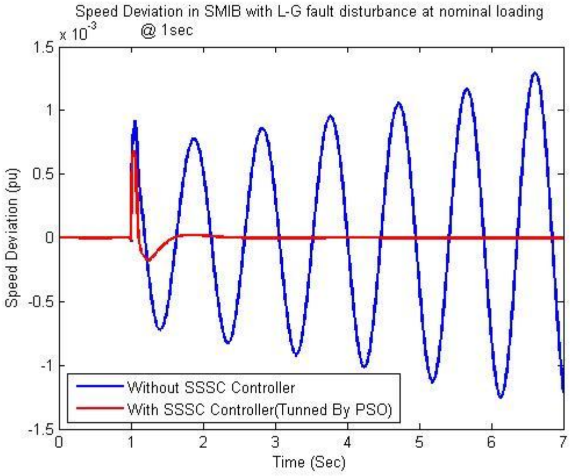

Fig. 12 Speed deviation in SMIB for L-G fault with & without SSSC controller at nominal loading

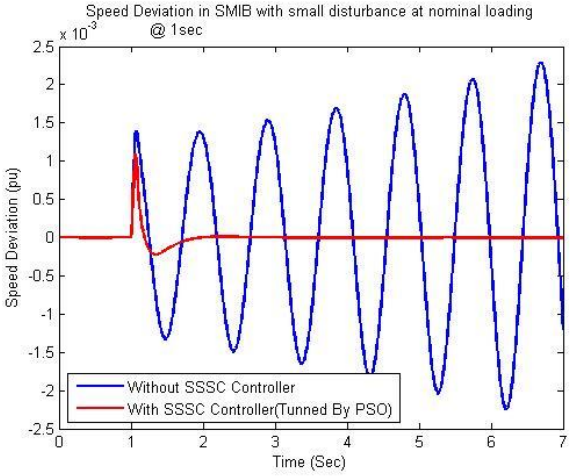

Fig.13 Speed deviation in SMIB for small disturbance with and without SSSC controller

II. Light Loading

The robustness of SSSC controller for different operating conditions is checked by changing the generator loading from nominal to light. For light loading condition ($P_e = 0.5$ pu, $\delta_0 = 22.9^0$) the SMIB system is subjected to balanced, unbalanced and small disturbances. The Simulation results provide the response of the system under various contingencies.

From fig.14 to 19 shows various wavefom depicting the simulation results of the SMIB system at light loading without and with PSO tuned controller for three phase fault,L-L-G fault,L-L fault,L-G fault ,small disturbance. It comes out that the PSO optimized SSSC based controller improves the system stability by damping out the oscillations and enabling the system to settle down quickly after various fault. whereas the system without controller takes longer time to settle down.

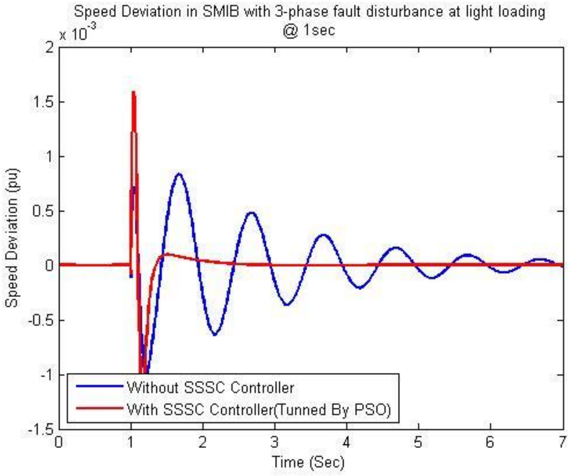

Fig. 14 Speed deviation in SMIB for 3-phase fault with & without SSSC controller at light loading

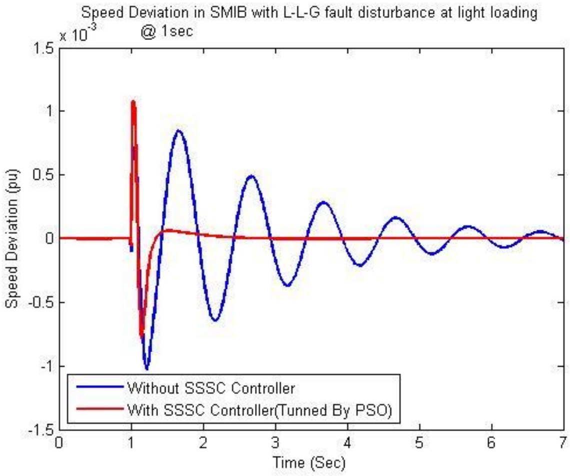

Fig. 15 Speed deviation in SMIB for L-L-G fault with & without SSSC controller at light loading

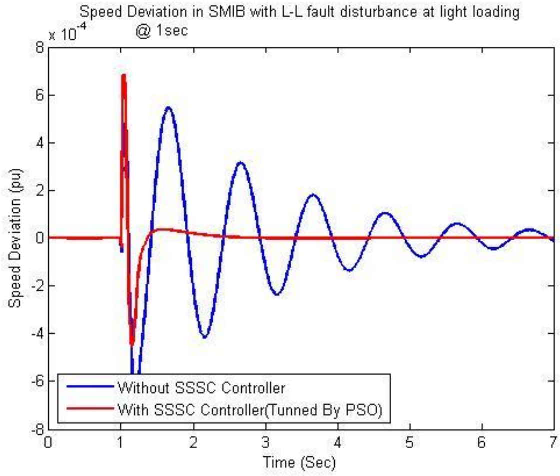

Fig. 16 Speed deviation in SMIB for L-L fault with & without SSSC controller at light loading

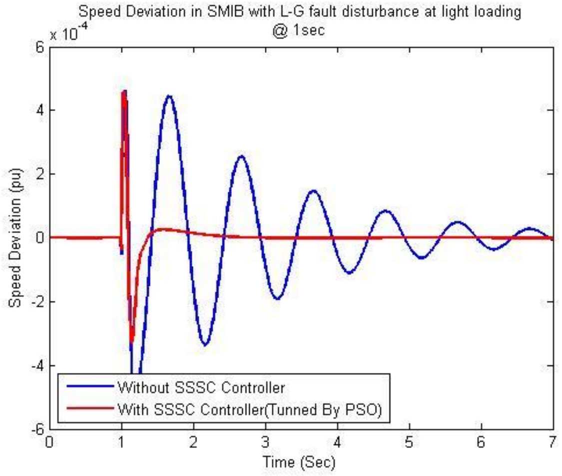

Fig. 17 Speed deviation in SMIB for L-G fault with & without SSSC controller at light loading

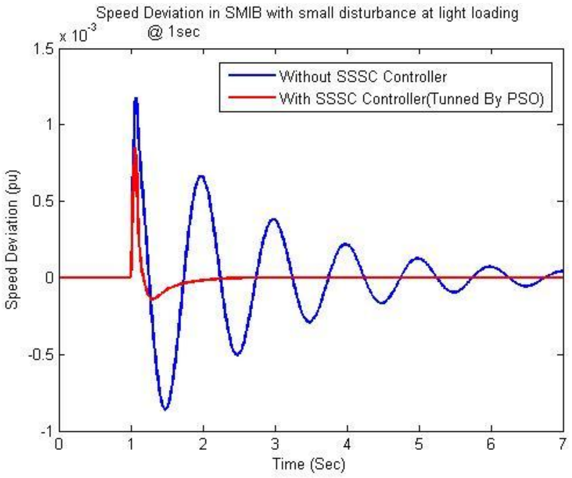

Fig. 18 Speed deviation in SMIB for small disturbance with & without SSSC controller at light loading

III. Heavy Loading

To examine the robustness of SSSC controller the loading condition is changed to heavy loading (Pe = 1.0 pu, $\delta o=60.7^0$). The speed deviation response of system for different balanced & unbalanced fault is obtained by simulation.

From fig.19 to 23 shows various wavefom of the simulation results of SMIB system at heavy loading without and with PSO tuned SSSC controller for three phase fault, L-L-G fault,LL-G fault ,small disturbance. It can be seen from the simulation results that the system with SSSC controller settles quickly whereas the system without controller is unstable because of insufficient damping. Hence the SSSC controller tuned by PSO is effective even for heavy loading condition.

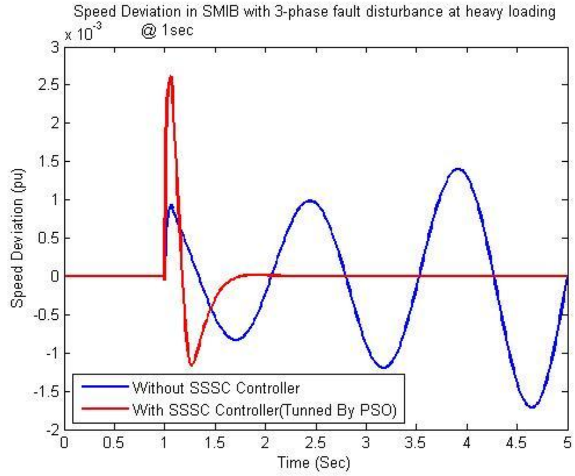

Fig. 19 Speed deviation in SMIB for 3-phase fault with & without SSSC at Heavy Loading

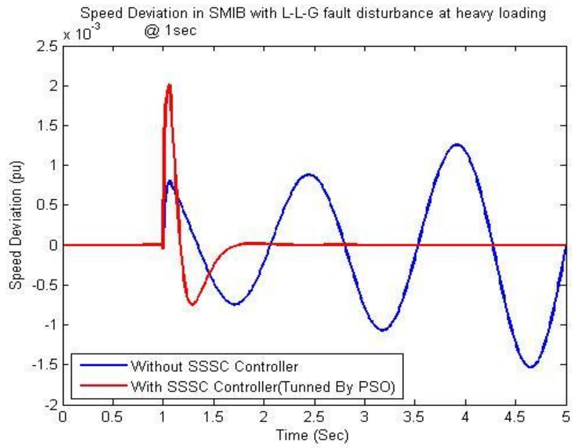

Fig. 20 Speed deviation in SMIB for L-L-G fault with & without SSSC controller at heavy loading

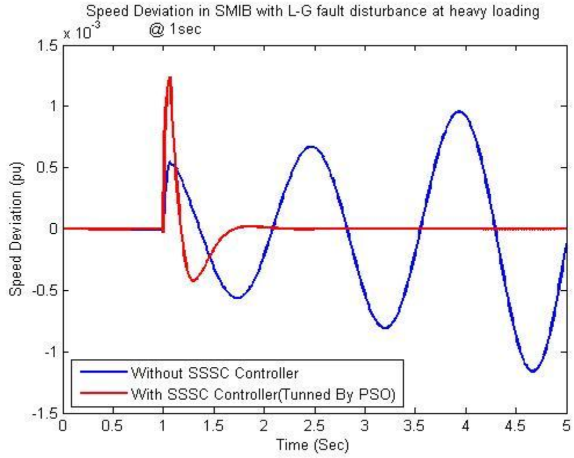

Fig. 21Speed deviation in SMIB for L-G fault with & without SSSC controller at heavy loading

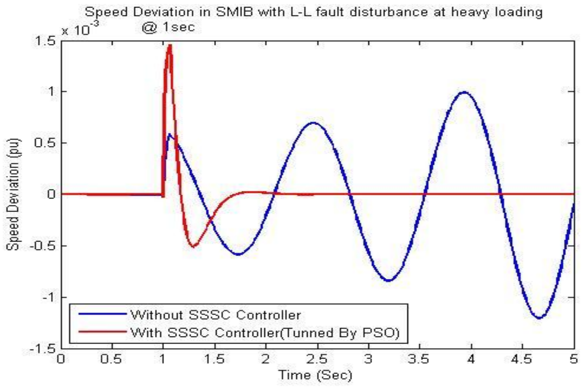

Fig. 21Speed deviation in SMIB for L-L fault with & without SSSC at Heavy Loading

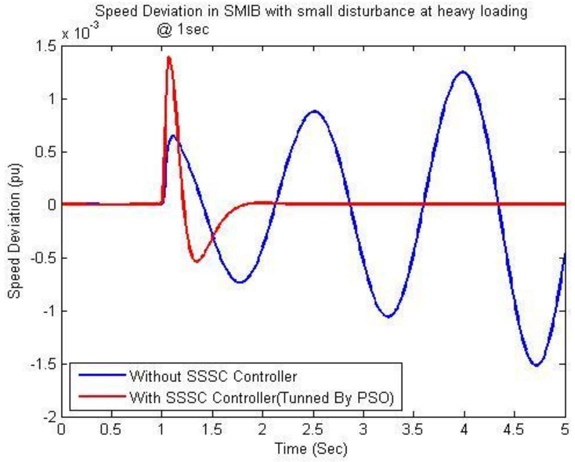

Fig. 22 Speed deviation in SMIB for small disturbance with & without SSSC controller at heavy loading

IV. Comparision Table-1 at SMIB System at without and with PSO Tuned SSSC Controller

S.N	Operating Condition	Fault	Without SSSC controller (Settling time)	With PSO tuned SSSC controller (Settling Time)
1.	Nominal Loading	3-Phase	Unstable	2.0146
		L-L-G	Unstable	2.0399
		L-L	Unstable	2.0647
		L-G	Unstable	2.0800
		Small disturbance	Unstable	1.8340
2.	Light Loading	3-Phase	Highly Oscillatory	2.0838
		L-L-G	Highly Oscillatory	2.1131
		L-L	Highly Oscillatory	2.1496
		L-G	Highly Oscillatory	2.1911
		Small disturbance	Highly Oscillatory	1.9936
3.	Heavy Loading	3-Phase	Unstable	1.6564
		L-L-G	Unstable	1.6616
		L-L	Unstable	1.6466
		L-G	Unstable	1.6505
		Small disturbance	Unstable	1.7551

Condition 2:- Multi Machine System

In the further approach the performance of PSO optimized SSSC damping controller is evaluated on a two machine system for damping the inter area mode of oscillations. The two machine system considered comprises of two generators M1 and M2. After a disturbance the two machines swing with respect to each other and hence inter-area oscillations are originated. The oscillations originated between two machines M1 & M2 after a disturbance are inter-area oscillations. The effectiveness of PSO tuned SSSC controller is inspected under different contingencies whose simulation results are discussed below.

In fig. 23 to 26 the inter-area oscillations in a two machine system for three phase fault,L-L-G fault, L-L fault,L-G fault and small disturbance with and without PSO tuned SSSC controller are shown. It can be clearly seen from fig.22 to that in absence of controller the system is quite unstable as the oscillations sustain because of insufficient damping by system whereas the PSO tuned SSSC controller provides good damping and system settles down Hence the controller is effective in improving the system stability.

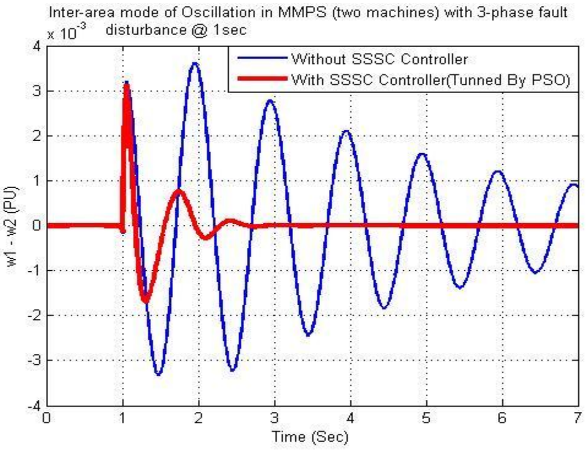

Fig. 23 Inter-area mode of oscillation in two machine system with & without SSSC controller for three phase fault

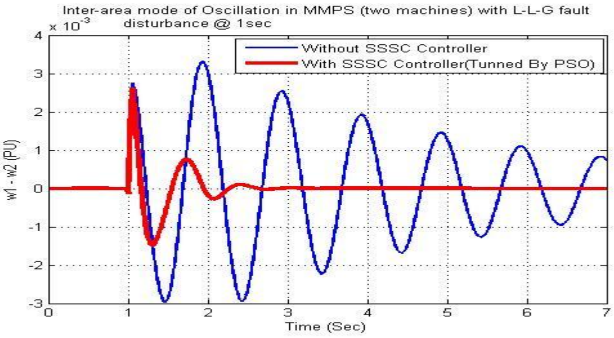

Fig. 24 Inter-area mode of oscillation in two machine system with & without SSSC controller for small disturbance

Fig. 24 Inter-area mode of oscillation in two machine system with & without SSSC controller for L-L-G fault

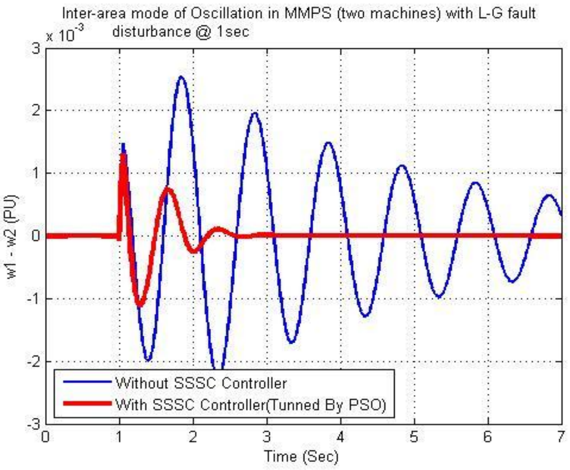

Fig. 25 Inter-area mode of oscillation in two machine system with & without SSSC controller for L-G Fault

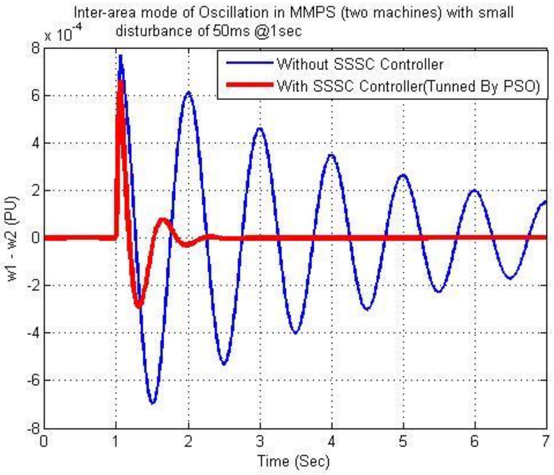

Fig. 26 Inter-area mode of oscillation in two machine system with & without SSSC controller for Small Disturbance

V. COMPARISION TABLE-2 AT MULTIMACHINE SYSTEM AT WITHOUT AND WITH PSO TUNED SSSC CONTROLLER

S.N	Fault	Without SSSC controller (Settling time)	With PSO tuned SSSC controller (Settling Time)
1.	3-Phase	Highly Oscillatory	2.5195
2.	L-L-G	Highly Oscillatory	2.5225
3.	L-L	Highly Oscillatory	2.5203
4.	L-G	Highly Oscillatory	2.5076
5.	Small disturbance	Highly Oscillatory	2.1173

VI. CONCLUSION

This paper has proposed the PSO technique for designing the SSSC based damping controller so as to improve the stability of a SMIB system & multimachine system. The dynamic performance of the controller was evaluated on different loading conditions and contingencies. The simualtion studies were carried out on MATLAB/Simulink. The simulation results presented depicted that PSO tuned SSSC controller effectively damps out the power system oscillation and help the system to settle down quickly as compared to the system without controller as shown in table 1 and 2. The simulation results concluded that the proposed PSO optimized SSSC controller greatly enhances the system stability.

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